SOUND INTENSITY PROBE CALIBRATOR FOR FIELD USE: CALCULATING THE SOUND FIELD IN THE CALIBRATOR USING BOUNDARY ELEMENT MODELLING

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ABSTRACT
The newest generation of sound intensity measurement equipment is small and light enough to be hand-held when used for measurements in the field. This increases the need for field verification of the equipment. Field verification must be easy to perform and should not require the equipment to be taken apart. Therefore it was decided at Brüel & Kjær to develop an intensity probe calibrator that could be used for the two-microphone intensity probe as it is, without dismounting the spacer. The geometry of the cavity of the calibrator with probe is rather complex, and it turned out that a simple model based on geometric considerations could not be made for predicting the acoustic properties of the calibrator. Therefore a Boundary Element Model of the calibrator cavity was developed and successfully used in the design of the calibrator. The calculations are shortly described, and the sound fields in the coupler with different cavity geometries and source configurations and the corresponding microphone responses are discussed.

INTRODUCTION

The newest generation of sound intensity measurement equipment is small and light enough to be hand-held when used for measurements in the field. The hand-held Brüel & Kjær Investigator Sound Intensity System Type 2260E/3595 is a good example of such measurement equipment. As in all measurements, the equipment for sound intensity measurements must be calibrated and verified before and after use. While in the laboratory it is not so important how the calibration is made, field calibration and verification must be easy to perform and should not require the equipment to be taken apart. Since this is not the case with sound intensity calibrators available until now, it was decided at Brüel & Kjær to develop a new intensity probe calibrator for field use. The design goals for the calibrator were: i) that it could be used for the Brüel&Kjær ½ two-microphone intensity probe as it is, without dismounting the spacer, ii) that it should be usable for absolute sensitivity calibrations as well as for pressure residual intensity index verification, and iii) that it should fulfil the requirements of International Standards IEC 60942 Type 1 and IEC 61043 Class 1.

A prototype for the new calibrator was designed based on classical, 'sound' acoustical considerations, e.g. symmetry, as small a volume as feasible around the probe. The design of the prototype was not far from the design of the final Brüel & Kjær Sound Intensity Calibrator Type 4297, but it turned out to work in a much smaller frequency band than expected. The unexpected behaviour was intensively discussed and a number of modifications of the prototype were made. The behaviour could not be explained by means of any suggested geometrical, lumped parameter or impedance considerations and no significant improvements were achieved with the modifications. Therefore it was decided to make a numerical model in order to find an explanation of the behaviour of the sound field in the coupler and to see if there were any possibilities of improvement. Since one of the authors, Vicente Cutanda, at the same time was working with Boundary Element Modeling, BEM, of the interior of microphones, a model of the coupler could be implemented fast with his software.

GEOMETRY

The calibrator consists of an axisymmetrical coupler cavity where the complete probe with spacer can be inserted. Basically, the coupler is a cylindrical cavity in which the intensity probe is placed with mutual symmetry axis and symmetry plane. In the prototype the coupler cavity was connected to another cavity with the sound source and a reference microphone through a small hole in the wall midway between the microphone diaphragms. In the final design the sound source is a part of a ring source situated in the coupler wall midway between the microphones and connected to the cavity through a slit. The cavity in the final design is also connected to another cavity with a reference microphone, but that is of minor importance in this context.

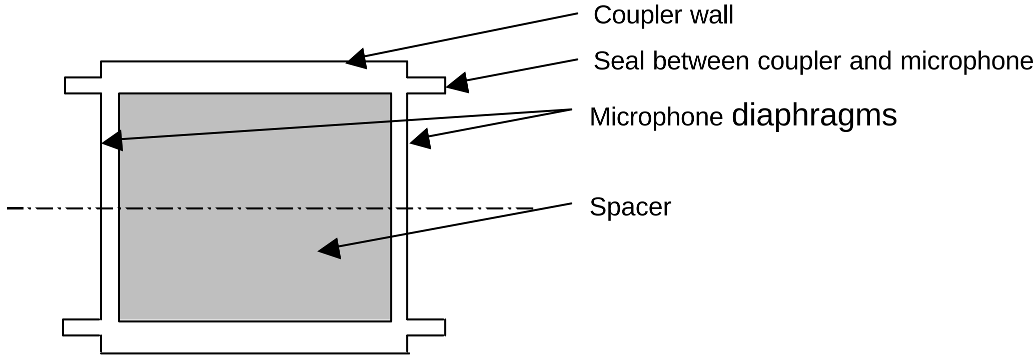

Figure 1. The coupler geometry defined for the calculations, see also figure 2.

CALCULATIONS

The BEM method used for the calculations was the direct collocation method in a formulation for axisymmetric bodies [1] with an improved calculation method for near-singular integration [2]. The actual formulation used allows for the calculation of non-axisymmetric sound fields by using a cosine expansion of the acoustical variables, i.e. pressure, particle velocity and excitation [3]. The terms in the expansion represent a sound field with an increasing number of nodelines. The first term, m=0, represents the axisymmetric part of the sound field and the following terms represent the non-axisymmetric part of the sound field. In this case, a non-axisymmetric velocity distribution on the boundary was used for the excitation. No losses were taken into consideration in the calculations, and the microphone diaphragms were assumed to be blocked. Calculations were made for a wide variety of dimensions and shapes within the basic geometry of the coupler cavity. Here a few of the calculations are presented so as to demonstrate the influence of the variations and the important results. In the examples the sound source is a half ring source in the coupler wall at the symmetry plane of the probe spacer (in the middle of the coupler). Also, one of the microphones is slightly displaced from its correct position so that the gaps between the spacer and the diaphragm are different at the two microphones.

Figure 2. Photographs of the final calibrator. The probe is a ½ probe with a 12 mm spacer. The slit with the sound source is seen in the middle of the coupler cavity.

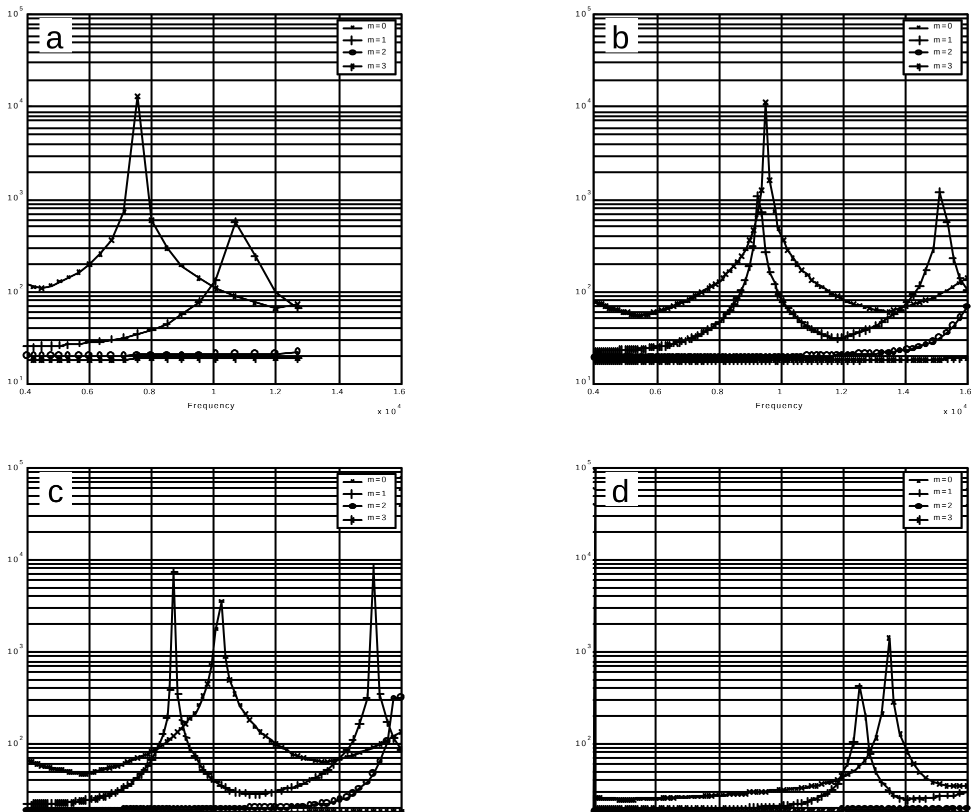

Figure 3. Coupler with different diameter and with and without spacer. Half-ring source. Condition number plots for the first four terms in the cosine expansion of the sound field. a: 7.2 mm with spacer. b: 8.0 mm with spacer. c: 8.5 mm with spacer. d: 8.0 mm without spacer.

The condition number of the coefficient matrix is a convenient means to locate the eigenfrequencies of the coupler [4]. This is due to the instability generated in the system of equations in the vicinity of such eigenmodes. Since the condition number is a measure of the system ill-conditioning, it presents maxima at those frequencies. In figure 3 the condition numbers are shown for the system of equations for the first four terms of the cosine expansion. Whereas the eigenfrequencies of the configurations with the spacer do not correspond in a simple way to the dimensions of the coupler, the eigenfrequencies for the configuration without the spacer corresponds closely to what must be expected for a cylindrical cavity. With the spacer the frequency of the axisymmetric modes increases with increasing diameter while the frequency of the non-axisymmetric modes decreases with increasing diameter. The calculated sound fields in the coupler at frequencies close to the eigenfrequencies shown in figure 3 are for the modes below 10 kHz in figures 4 to 7. In the narrow coupler the lowest eigenmode is an axisymmetric longitudinal mode. Note, that the phase is opposite at the two microphone diaphragms. This will not be the case if the gaps at the microphones are exactly same. However, the sound field is

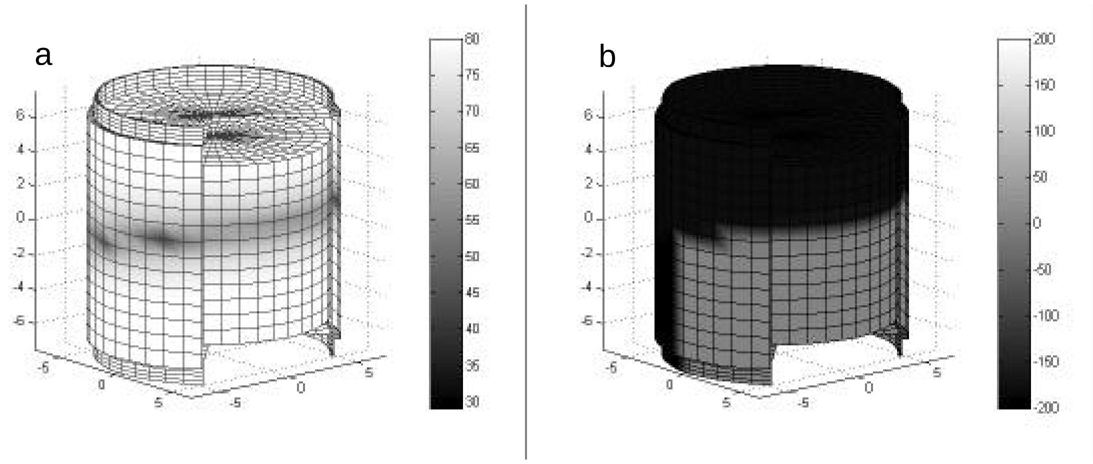

Figure 4. *Sound field at 7.55 kHz in ∅ 7.2 mm coupler with spacer and half-ring source. a: modulus in dB, b: phase in °.*

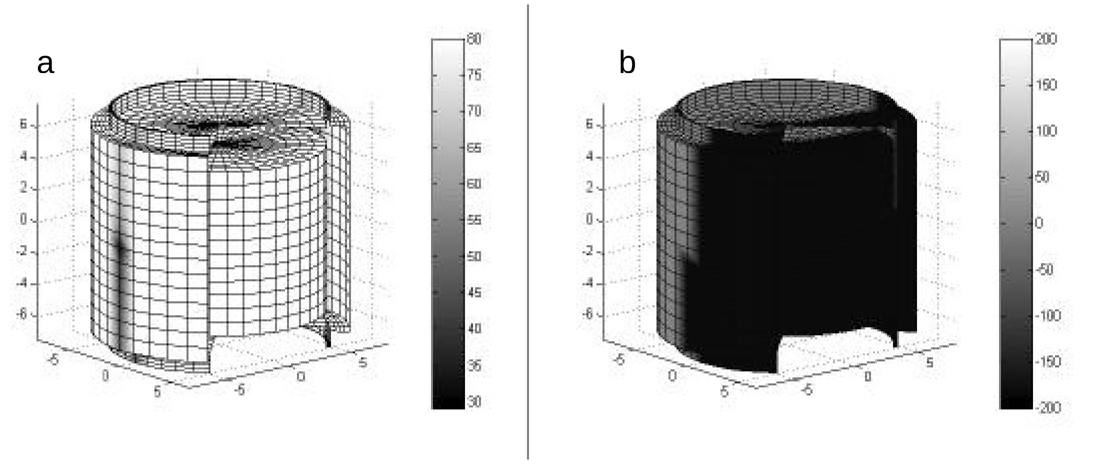

Figure 5. *Sound field at 9.38 kHz in ∅ 8.0 mm coupler with spacer and half-ring source. a: modulus in dB, b: phase in °.*

unstable at this frequency and will change with any small change in the dimensions. The lowest modes of the 8.0 mm and 8.5 mm coupler are transversal modes. The sound field is in opposite phase in the two sides of the coupler and the sound pressure level is high. The 8.0 mm coupler has a longitudinal mode at a slightly higher frequency. The sound field at that frequency is a combination of a transversal and longitudinal wave.

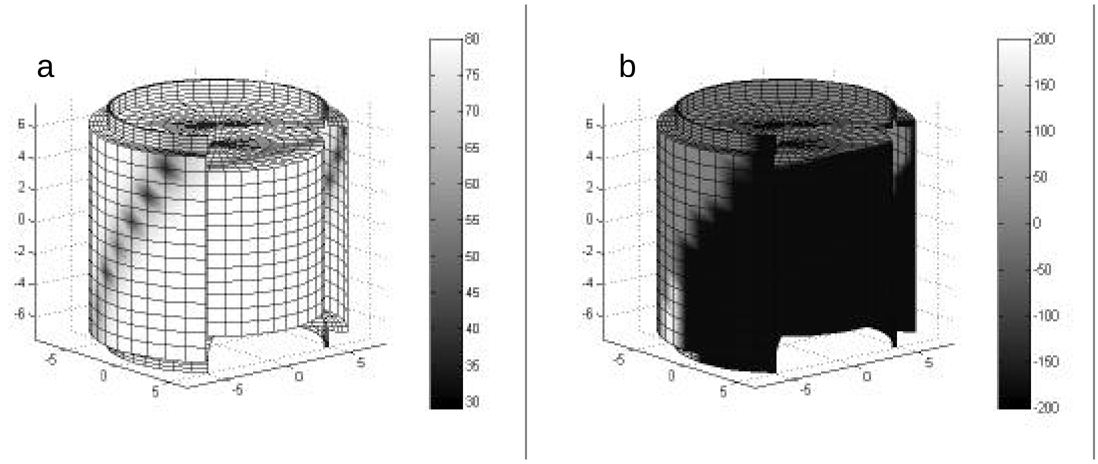

Figure 6. Sound field at 9.51 kHz in ∅ 8.0 mm coupler with spacer and half-ring source. a: modulus in dB, b: phase in °.

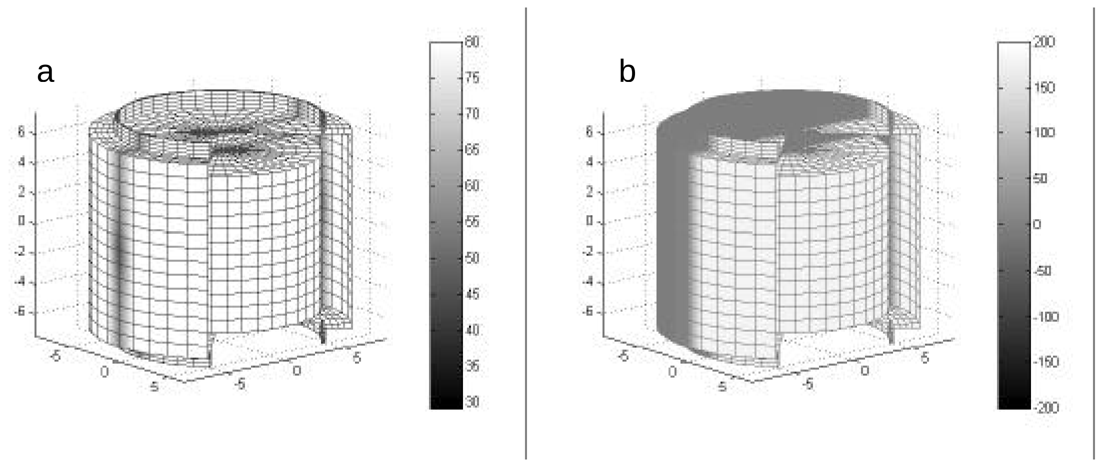

Figure 7. Sound field at 8.72 kHz in ∅ 8.5 mm coupler with spacer and half-ring source. a: modulus in dB, b: phase in °.

DISCUSSION

As shown above, the sound field in the coupler with the same excitation changes rapidly with the coupler diameter in a way so that there is an optimal diameter for the coupler cavity with the given geometry. With a small diameter and thus a narrow gap between the probe and the coupler walls the axisymmetric modes appear at lower frequencies than the non-axisymmetric modes. With increasing diameter the frequencies of the axisymmetric modes increase while the frequencies for the non-axisymmetric modes decrease. The optimum diameter is the diameter where the modes have the same frequency since this gives the highest bandwidth without resonances and thereby a stable sound field. The changes of the sound field with diameter illustrates why the modes of the cavity with the spacer cannot be found with simple geometrical considerations. The cavity cannot be divided into substructures that can be identified as being cavities, tubes or transmission lines. Rather, all parts of the cavity with the spacer are something in between such acoustical elements.

The process in the development project on which this paper is based clearly shows the value of numerical calculation methods. The advantage most often mentioned in the literature is the possibility of making many virtual prototypes, that is, testing many variants of a design. However, a more important advantage of using the calculations here is that a deeper understanding of the sound field in the coupler and the problems in the development were obtained. Based on the calculations described in the previous section the coupler in the intensity probe calibrator was designed with a diameter of 8.0 mm. In the first design of the coupler the diameter was chosen to be as small as practically possible. It was actually discovered before the calculations were taken into use that some, but not all, couplers with a larger diameter had a better performance, but since there were no clear explanation and since it is not practically possible to make several prototypes this did not lead to a conclusion on the design. Furthermore, even more prototypes may not have led to the final design since the information on the sound field and thereby the explanation of the differences could only have been obtained with highly complicated measurements on many prototypes.

The microphone responses were also considered during the development of the coupler. In principle the microphones are only sensitive to the axisymmetrical modes of the sound field and therefore non-axisymmetric modes should not influence the performance. Although any real microphone may exhibit some minor sensitivity to non-axisymmetrical modes this is probably not the only reason the coupler does not perform well when non-axisymmetric modes are present. Rather, because the sound field varies so much in the coupler near the eigenfrequencies, the axisymmetric part of the sound pressure in the real coupler may very well be a little different at the two microphones, and this difference would be measured even with perfect microphones. For this reason it is not possible directly to compare the calculations with measurements with the probe in the coupler and therefore such comparisons are not shown here. What could be seen was that the couplers performed well at frequencies up to around 2/3 of an octave below the first eigenfrequency of the coupler. It should be remembered that in this context good performance means less than 0.1 dB and 0.2° difference between the two microphones at frequencies around 5 kHz.

The Sound Intensity Calibrator Type 4297 that is the result of the development project described here is very close to the fulfillment of the design goals initially set up for the project. Without the spacer the calibrator fulfils the requirements of IEC 61043 Class 1. The pressure-residual intensity index of the sound field is larger than 24 dB in 1/3 octave bands from 50 Hz to 6.3 kHz. However, with the spacer the pressure-residual intensity index is slightly lower than 24 dB in the 6.3 kHz 1/3 octave band. The calibrator can still be used for verification of the equipment with the spacer in daily use, but it does not fulfil the standard completely. The numerical calculations showed that this was the best performance that could be achieved for a coupler where the probe could be inserted without dismounting the spacer.

CONCLUSIONS

In this paper it has been demonstrated how BEM calculations successfully led to a working design of a sound intensity calibrator. The sound field in the coupler could not be predicted with “classical” methods. The calculations did not only lead to a successful design but also gave a understanding of the behaviour of the sound field in the calibrator that could not be obtained without the calculations.

The calculations described in this paper led a development project from failure into success. Numerical calculations are certain to be developed and used in future acoustical design projects at Brüel & Kjær.

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